Rainfall influence on plot-scale runoff and soil loss from repeated burning in a Mediterranean-shrub ecosystem, Valencia, Spain

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Abstract

The effect of a repeated burning on soil hydrology and erosive parameters was studied on a Mediterranean forest soil (Rendzic leptosol) with the aim of identifying the effects of the fire and climatic parameters related to the post-fire runoff and soil loss. The study was carried out in an Experimental Permanent Field Station (La Concordia), close to Valencia (Spain). This field station is located on a calcareous hillside facing SSE, and is comprised of nine erosion plots (20×4 m). Firstly, experimental fires were performed in June 1995 with two fire treatments (T1 or high severity fire and T2 or moderate severity fire) and a control one (unburnt, T3). The repeated fire (low severity) was carried out in July 2003. The studied period was focused from 18 months before the repeated fire (July 2003) until 18 months after it. Rainfall characteristics of each single event were recorded, which allowed us to statistically distinguish four time periods according to the rainfall intensity and duration: periods I (March 2002 to May 2003) and III (December 2003 to early May 2004) with low intensity and long duration rainfalls, and periods II (June 2003 to November 2003) and IV (late May 2004 to December 2004) with high intensity and short duration rainfalls. Before the 2003 fire, the partial recovery of soil and vegetation from the previous burning in 1995 led to a diminution in the runoff rates (6.5 L m^{-2} in burned plots and 1.8 L m^{-2} in unburnt ones). Six months later (period II), runoff increased in one order of magnitude (23.9 L m^{-2} in burnt plots and 1.1 L m^{-2} in the unburnt ones) due, in part, to the short time elapsed from fire until high intensity rainfalls. These differences in runoff production were maintained during the whole post-fire period.

Fire effects were reflected in the erosion rates. Soil losses prior to the 2003 fire, in both fire treatments and in the control one, were scant relative to post-fire levels. However, six months after the repeated fire (period II) and almost one year later (period IV), soil losses increased into two orders of magnitude coinciding with the post-fire bare soil augment. The repeated fire impact and rainfall intensity magnified runoff and soil loss. Significant linear relationships between rainfall intensity, runoff and soil loss, were obtained for the burned plots. In the

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burned areas, rain intensities increased to 20 mm h^{-1} augmenting the runoff and soil loss in one and two orders of magnitude, respectively.

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Keywords: Repeated fire, Mediterranean, soil, runoff, erosion, rain intensity.

1. Introduction

Forest fires in Mediterranean ecosystems have occurred for centuries, creating the current mosaics of vegetation communities (Trabaud, 1994), fire being a part of the landscape modelling. In the last three decades, forest fire frequencies have gradually increased. This tendency reflects the possibility of fire incidence on areas that are in a recovering stage from previous fires, modifying the vegetation patterns and thus the soil hydrology. The elimination of the vegetation, which is often structured in a spotted or banded spatial configuration, affects both, the evapotranspiration and soil infiltration processes that can influence water storage (Neary and Ffolliot, 2005), a key property to understand the evolution of runoff and erosion processes (Calvo-Cases et al., 2003).

On the other hand, in the western Mediterranean area the majority of wildfires usually take place in the dry summer period (Andreu et al., 2001), held by the high temperatures reached at soil surface and by the low biomass and soil moisture conditions. In these circumstances, soil water content reaches minimum values making forest litter consumption by fire easier. This process promotes structural changes in the soil surface physical properties (Andreu et al, 2001); in fact, hydrological and erosive parameters can be increased as much as one to three orders of magnitude (Inbar et al., 1998; Benavides-Solorio and MacDonald, 2001). In that way, the repeated fire incidence in Mediterranean landscapes could lead the soil system to a degradation stage.

After a fire in the zone of Mount Carmel (Israel) with comparable climatic conditions, soil type and slope steepness, Inbar et al. (1998) suggested that the time to return to pre-fire erosion values was five to ten years. Moody and Martin (2001a), proposed three to four years as the relaxation time for sediment concentration. Time to reach the soil steady-state conditions

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depends on a wide range of factors that can control runoff and erosion rates, including fire severity, percentage of bare soil, rainfall intensity, soil water repellency, soil texture, slope and aggregate stability (Inbar et al., 1998; Pierson et al., 2001). In addition, climate conditions are other key factors in Mediterranean environments. A repeated fire impact, when the ecosystem is in a recovery phase, magnifies into two orders of magnitude the soil losses during the first rainy season (Campo et al., 2006). Studies in other Mediterranean areas have identified the first two rainy seasons as the most critical periods for post-fire flooding and sedimentation (Robichaud et al., 2000).

Rubio et al. (2003), suggests that one of the most useful ways to study the fire effects on the soil system is carrying out experimental fires in plots. With this approach, it is possible to know and measure the soil conditions before, during and after the fire experiment, improving the knowledge about the hydrology and erosive parameters. Following this approach, experimental fires with time series of data of at least two years can help to identify the effect of a repeated fire impact on the water erosion processes. The aim of this research in a Mediterranean-shrub ecosystem in Spain is: (1) to monitor the evolution of runoff and soil loss, 18 months before and during the first two rainy seasons after a repeated fire; and (2) to identify the effect of climatic parameters involved in the runoff and soil loss processes.

2. Study area and methods

2.1. Study area and soil characteristics

In 1994, the Experimental Field Station of La Concordia was set up in a forested range area ceded by the Valencian Government (Generalitat Valenciana). It is located 575 m above sea level, on a hillside facing SSE with an average slope of 30% or 17º (Fig. 1). The shrubland vegetation was composed of *Globularia alypum, Rosmarinus officinalis, Ulex parviflorus, Cistus clusii, Thymus vulgaris, Rhamnus lycioides, Stipa tenacissima,* and *Quercus coccifera* (Gimeno-García et al., 2000), being this a schlerophyllous shrub cover regenerated in a patchy mosaic pattern after a wildfire in 1978.

The geology is dominated by Triassic, Jurassic and Cretaceous rocks. The field station is underlain by carbonate marine sedimentary rocks of the Jurassic period (IGME, 1977). It comprises a micritic grey cracked limestone that developed a soil of Rendzic leptosol (FAO-UNESCO, 1988) or Rendzinas (WRB, 2006). The texture of the soil is sandy-loam and the aggregate stability ranges between 32–40%. The soil organic matter content is around 10%, and the soil water retention capacity is ~22%, with a pH of 7.5. Soil profile shows a variable depth, no more than 40 cm, high superficial stoniness (~65%), good drainage and significant microbiological activity showing frequent and discontinuous soil pores (Rubio et al., 2003).

The mean annual precipitation in the area is around 400 mm, with two maxima (autumn and spring), and a dry period in summer. The average temperatures range between 13.3ºC in the coldest month (January) and 25.8ºC in the hottest one (August).

2.2. Experimental set up

The field station has nine erosion plots. Each plot is 4 m wide and 20 m long (80 m^2), with similar soil, slope gradient, rock outcrops and vegetation cover characteristics. The selection of each plot was made after intensive soil and vegetation monitoring (number of individuals of each specie, height and diameter), and morphology patterns, based on 58 slope transects disposed every 2 m (Andreu et al., 2002; Rubio et al., 2003).

Plots were oriented parallel to the slope and bounded by bricks. At the foot of each plot, a 2 m wide collector ran into a 1500 L tank to record all runoff and sediment produced during each rainfall event. Inside each tank, there was a 30 L tank into which water and sediment first flow, to permit accurate measurement when runoff was small.

Runoff generation and sediment production were monitored in each erosive rainfall event occurred during the studied period (2002–2004). When the total volume of runoff and sediments were <30 L, the 30 L deposit was used to measure those parameters. When the volume of water and sediments exceeded 30 L, they were poured, mixed and homogenized into the 1500 L deposit. Then, a 1 L mixed sample was taken from three different depths, depending on the height and volume of the runoff in the 1500 L tank. This mixed sample was filtered through a pre-weighted 5 μm porous diameter filter paper to separate sediment from water. The filter with the sediments were dried at 105ºC for 24 hours and weighed to determine the sediment mass in each sample. The total sediment produced was calculated by extrapolating the sediment in the 1 L sample with the total volume of runoff collected.

The climatic data were collected at an automatic meteorological station placed half way up the slope in the central part of the field station. A CS700 tipping bucket was used to record rainfall characteristics. Rainfall volume (mm), intensity (I_{30}, the maximum volume of precipitation occurring in 30 minutes, in mm h^{-1}) and duration (min) were recorded for each rainfall event occurred between 2002 and 2004. Erosive rainfall events were only considered if runoff is registered in the tanks.

2.3. Fire experimental history and design

In 1995, a random design of three plots with two different fire severity treatments was used. The remaining three plots were maintained unburnt to be used as control (T3). The different fire severities were achieved by adding different amounts of biomass: 4 kg m^{-2} for the high severity fire (T1) and 2 kg m^{-2} for the moderate severity fire (T2). The amount of biomass were established determining the relationship between fuel load, height and biomass compaction based on studies of Papió and Trabaud (1991), and calculations were based on laboratory experiences on heat capacity of different Mediterranean shrub species (Gimeno-García et al., 2007). The added biomass was taken from the surrounding area and its quantity was calculated using a modification of the method proposed by Etiene and Legrand (1994).

The first experimental fires were carried out under field conditions on the 20th and 21st of June, 1995. The fire progressed upslope and their patterns were uniform in all the plots. The temperatures on the soil surface and their duration were measured in 1995, and also in 2003 fires by means of thermosensitive paints and thermocouples (Gimeno-García et al., 2007). In 1995, statistically significant differences, between T1 and T2, were observed on the average soil surface temperatures (439ºC and 232ºC, respectively) and on the average values of residence time in soil of temperatures greater than 100ºC (36 minutes in T1 and 17 minutes in T2) (Gimeno-García et al., 2000, 2004).

In 2003, the natural development of vegetation in T3 showed a notable biomass increase, from 0.45 to 0.90 kg m^{-2}. In T1 and T2, the post-fire regenerated biomass reached 0.5 and 0.4 kg m^{-2}, respectively (Gimeno-García et al., 2007), an enough quantity of biomass to set a date for a repeated fire impact. On the other hand, the percentage of vegetation cover before 2003 fires was 30–35% in T1 and T2, and 45% in T3.

The repeated fires were performed on the 17th and 18th of July, 2003. In this way, and to simulate the natural characteristics of a repeated fire, the six plots burned in 1995 were burned again without biomass addition, except a small quantity of straw (0.25 kg m^{-2}) sparsely added to obtain fire continuity on the slope.

The average temperature on the soil surface reached 170ºC, and the mean values of residence time in soil of temperatures greater than 100ºC, for all the plots, was around four minutes. With this fire behaviour, and according to the classification established by DeBano et al. (1998), these repeated fires could be classified as low severity. In spite of the 2003 low fire severity, we have conserved the plots classification from 1995 fires (T1, T2 and T3) to differentiate between treatments in this study.

2.4. Statistical analyses

Analysis of variance (ANOVA) was performed on the rainfall characteristics (rainfall volume, intensity and duration) in order to define the rainy periods. When significant differences were detected among means, the minimum significant difference were calculated using Tukey's test (post-hoc pair wise comparison) at $p < 0.05$. This analysis was also applied to detect differences in the hydrological and erosive processes between fire treatments, and to compare their variations between pre- and post-fire periods. Standard statistical bivariate correlation analyses were applied, at 95% and 99% significance levels, between the rainfall parameters, runoff and soil loss, to determine the effects of rainfall characteristics on erosion processes. All computations were made using the SPSS v.15 package (www.spss.com).

3. Results

3.1. Rainfall characteristics

In the studied period of 2002–2004, a total of 37 erosive rainfall events with runoff production were registered. The rainfall characteristics allowed us to differentiate four different periods based on the intensity, volume and duration of the rainfall events: I) year 2002 until spring 2003 (March 2002 to May 2003), with low intensity rainfalls; II) summer and autumn of 2003 (June 2003 to November 2003), with intense rainfall events such as one in August 2003, where ten days after the experimental fire, a single erosive rain event reached an I_{30} of 65.4 mm h^{-1}. In addition, the next three rainstorms reached I_{30} from 20 to 40 mm h^{-1}; III) winter 2003 to spring 2004 (December 2003 to early May 2004), characterized also by low intensity rainfall events; and IV) summer and autumn 2004 (later May 2004 to December 2004), with the highest rainfall intensities. In the late summer of 2004, after a period of scarce rains, two storm events of increasing rainfall intensity occurred, achieving I_{30} records of 35.6 mm h^{-1} and 91.9 mm h^{-1} (Table 1 and Fig. 2).

The runoff and sediment production in the burnt plots were strongly influenced by the peaks of rainfall intensity. In this way, in periods I and III, the thresholds to produce runoff and soil loss were 1.8 mm h^{-1} and 2.2 mm h^{-1}, respectively. While, in periods II and IV those thresholds were 3.4 mm h^{-1} for runoff and 4.6 mm h^{-1} for soil losses.

3.2. Hydrological consequences

Gimeno-García et al. (2007) observed that, in the experimental station, and one year after the former experimental fires in 1995, a 77% more runoff was produced in the burnt plots than in the control ones: 19.4 L m^{-2} yr^{-1} in T1, 14.7 L m^{-2} yr^{-1} in T2, and 3.8 L m^{-2} yr^{-1} in T3. Eight years after the 1995 fires, the soil and vegetation recovery favoured the disappearance of the large differences between fire treatments: 6.4 L m^{-2} in T1 and 6.6 L m^{-2} in T2.

However, between the burnt and the control treatments, the difference was still 70%: 6.5 L m^{-2} in the burnt plots and 1.8 L m^{-2} in the control ones (Fig. 3).

Once the repeated fires in 2003 were carried out, the runoff generation increased. Differences between fire treatments (T1 and T2) and control (T3) reached 95% at the end of period II, with 23.9 L m^{-2} of runoff yield in the burned plots and 1.1 L m^{-2} in the control ones. In the same way, the differences between fire severity treatments were also enhanced, and in T2 almost 12% more runoff than in T1 was generated: 22.5 L m^{-2} in T1 and 25.4 L m^{-2} in T2. The importance of the peak of rainfall intensity in runoff production was clear during the first rainfall event that occurred ten days after the 2003 fire (I_{30} of 65.4 mm h^{-1}). During this rainfall event, T1 and T2 yielded runoffs of 6.8 L m^{-2} and 9.6 L m^{-2}, respectively, which corresponded to 33% of the runoff generated in the whole period II. The control plots only produced 0.95 L m^{-2}. In addition to this early event, three consecutive rainfalls with I_{30} of 21 mm h^{-1}, 65.6 mm h^{-1} and 21.8 mm h^{-1} were recorded, and together with the former one they accounted for 76% of the runoff produced in the whole period II.

The runoff yield during period III was the lowest of the four 2002-2004 periods: 2.8 L m^{-2} in the burnt plots (average of T1 and T2) and 0.3 L m^{-2} in T3. These negligible yields were mainly due to the small rainfall volume during winter 2003 and spring 2004 (130 mm). In addition, the average I_{30} never exceeded 11 mm h^{-1}. Due in part to the rainfall characteristics, differences in runoff between the fire and control treatments fell in one order of magnitude (from 23.9 L m^{-2} in period II to 2.8 L m^{-2} in period III). Between fire treatments (T1 and T2), the difference was only 0.5 L m^{-2}: 2.5 L m^{-2} in T1 and 3.0 L m^{-2} in T2, an insignificant difference for the usual variability of experimental field measurements in Mediterranean landscapes.

On the other hand, the rainfall characteristics of periods II and IV were statistically comparable (Table 1). On both periods similar runoff were produced. In the summer and autumn 2004 (period IV), the runoff yield in T3 was low (1.8 L m^{-2}), whereas the values of T1 and T2 were high and similar: 27.7 L m^{-2} in T1 and 27.6 L m^{-2} in T2. Focussing on the two large storm events in this period, on the 4th and 6th of September, 2004 (I_{30} of 35.6 mm h^{-1} and 91.9 mm h^{-1}, respectively), the runoff generated in burnt plots, 25.5 L m^{-2}, represented

92% of the total runoff yield for the whole period. In the control plots, 1.6 L m^{-2} were collected, which corresponded to 90% of the overland flow measured in this period.

3.3. Soil losses

One year after the 1995 fire, the average soil loss in the burned plots was 4.3 T ha^{-1}: 5.6 T ha^{-1} in T1 and 3.2 T ha^{-1} in T2, while T3 only produced 0.085 T ha^{-1} (Gimeno-García et al., 2007). In contrast, before the 2003 repeated fire (period I), the sediment yielded in the burnt plots amounted to 0.021 T ha^{-1}, while in T3 it was negligible, 0.00005 T ha^{-1} (Fig. 4).

Immediately after the 2003 repeated fire (period II), the sediment produced increased substantially. Ten days after this fire, the burnt plots lost around 3.19 T ha^{-1} of soil in the first erosive rainfall event (I_{30} of 65 mm h^{-1}), while the control plots only lost 0.0044 T ha^{-1}. In the whole period II, total soil losses reached 4.05 T ha^{-1} in T1, 5.14 T ha^{-1} in T2, and 0.0068 T ha^{-1} in T3 (Fig. 4).

In period III, no appreciable soil losses were recorded in T3. In the same way, the burnt plots generated, on average, only 0.009 T ha^{-1}. These low rates can be explained by the weak rainfalls occurred in this period (Fig. 2).

In period IV, the erosion rates were similar to those obtained in period II. Differences of two orders of magnitude were reached between fire and control treatments. Sediment production in burnt plots was 3.64 T ha^{-1} (3.01 T ha^{-1} in T1 and 4.27 T ha^{-1} in T2), whereas in T3, soil losses were of 0.015 T ha^{-1}. The similar rainfall aggressiveness recorded in periods II and IV (high I_{30} values and short events duration, Table 1), revealed that the major erosion occurred during single rain events of high rain intensity (I_{30} > 20 mm h^{-1}). Concerning the rainstorms of the 4th and 6th of September, @@ (I_{30} of 35.6 and 91 mm h^{-1}, respectively), the sediment collected in the burnt plots was 3.6 T ha^{-1}, which represents 98% of the total sediment generated during the whole period IV. In the same way, in the control treatment these two consecutive rainstorms produced 0.015 T ha^{-1}, 99% of the soil loss in this period.

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3.4. Rainfall parameters related with runoff and sediment production

The correlations between rainfall parameters (volume, duration and I_{30}), and the runoff collected in the different periods are displayed in Table 2. In the whole study period (2002–2004), significant correlations between I_{30} and runoff were observed. However, the analysis between rainfall characteristics and runoff on each described period showed that in the former one (period I), runoff production in burnt plots were more controlled by the rainfall volume than by the average rainfall intensity, even though both parameters showed similar correlations. In period II, average I_{30} was positively correlated with runoff only in T2 and T3, although the statistical significance level for T1 was very close to 95% (R = 0.738 with p = 0.058). However, in period III the runoff levels were not correlated with rainfall parameters. During period IV, the runoff yields in the burnt and control plots were highly correlated with the average I_{30} and rainfall volume.

A key parameter related to soil losses was the rainfall intensity (Table 3). The correlations showed a high positive relationship, in all treatments, between average I_{30} and sediment production. Periods II and IV showed strong positive correlations between rainfall volume, average I_{30} and soil losses, when the most aggressive rainfall conditions appeared. Whereas, in periods when only weak rainfalls occurred (periods I and III) there were no statistically significant correlations between rainfall characteristics and sediment production.

Therefore, average I_{30} could be used as the parameter controlling sediment production after the 2003 experimental fire (period II). To the contrary, in periods I and III, there was no significant correlations mainly due to the low average I_{30} values recorded during these rainy seasons and thus, by the lack of soil loss in the plots.

After the repeated fire, average I_{30} and the erosive parameters show a linear correspondence with > 95% significance (Fig. 5). The I_{30} threshold of 20 mm h^{-1} favoured the magnification of the runoff and sediment yield in the burned plots. When the rainfall intensity exceeded this value, runoff increased by one order of magnitude compared to the control plots, whereas for sediment yield increased by two orders of magnitude (Fig. 5).

4. Discussion

4.1. Rainfall aggressiveness and runoff

The precipitation in the Mediterranean areas shows a wide inter-annual variability, with intense and prolonged dry periods in summer and heavy rainfalls in autumn. Meanwhile, forest fires have become a usual phenomenon during summer in many European Mediterranean countries (Andreu et al., 2001; Cerdà and Lasanta, 2005), due mainly to the low fuel moisture content and the increasing human activity pressure (tourism, second residences, etc.).

In this way, post-fire rainfall characteristics, such as rainfall intensity peaks in individual rainfall events, could influence runoff trends. The rainfall intensity variability at the La Concordia Experimental Station ranged from 1.8 to 91.8 mm h^{-1} during 2002–2004, being a level of 2.2 mm h^{-1} (Fig. 2) enough to generate runoff in the burnt plots. This I_{30} threshold to generate runoff is much lower than 10 mm h^{-1} defined by Inbar et al. (1998) in Mount Carmel, Israel, a comparable Mediterranean forest area characterized by similar bedrock (Jurassic limestone), soil type (Rendzina), and slope steepness (30%). Moody and Martin (2001b) also defined an I_{30} threshold of 10 mm h^{-1} to generate runoff but it depended on a wide range of factors such as vegetation cover, slope angle and elapsed time since fire.

In the study area, before the 2003 repeated fire, the rainfall characteristics in year 2002 showed the highest accumulated rainfall volume of the decade (556 mm), but with lower rainfall intensities (average I_{30} = 5.37 mm h^{-1} ; Fig. 2). This fact, together with the 30–40% vegetation recovery since 1995 and the negative exponential relationship between plant cover and runoff (Gimeno-García et al., 2007), facilitated a decrease in runoff rates until the year 2002–2003 (period I): 6.5 L m^{-2} in the burnt plots and 1.8 L m^{-2} in the control ones. Consequently, eight years after the 1995 fire, the runoff yield was reduced.

As reported by Andreu et al. (2001), the maximum runoff was reached during the early storms occurred after the fire event, being the fourth initial months the most critical period for runoff production (Rubio et al., 1995). It is reflected by the runoff generated in response to the rainfall event of the 30th July, 2003 (I_{30}= 65.4 mm h^{-1}), where 8.2 L m^{-2} were collected in the burnt plots (one order of magnitude greater than the control plots), while the total runoff in period II (summer□autumn 2003) was 23.9 L m^{-2}. In similar conditions, Andreu et al. (2001) picked up 1.5 L m^{-2} in response to a single rainfall event, which occurred five months after a natural fire in the same mountain range, and Gimeno-García et al. (2007) collected low runoff yields in the burnt plots (between 0.1 L m^{-2} and 0.35 L m^{-2}) in response to two rainfall events (I_{30} of 20.8 mm h^{-1} and 14.5 mm h^{-1}) occurred two months after the 1995 fire, when the soil surface was still covered by a thick layer of ashes and charred vegetation.

In 2003, the standing biomass present on the plots was much less than that before the 1995 fire (only 0.45 kg m^{-2}, with a percentage of vegetation cover between 30-40%; Gimeno-García et al., 2007), and the 2003 fire was a low severity one. Therefore, in contrast to the 1995 fire, the 2003 fire left the soil surface mainly bare and only covered by a very thin and discontinuous ash layer that was not enough to absorb drop impact. . This situation and the first rainfall event of high intensity (ten days after) together resulted in a runoff increase of at least one order of magnitude. Similar post-fire increase in erosion was also identified by Inbar et al. (1998), Benavides-Solorio and MacDonald (2001), and Kunze and Stednick (2006), in semiarid areas of Israel and USA.

4.2. Soil losses after the experimental fires

After the 1995 fire, the gradual soil and vegetation recovery contributed to decreased soil erosion (Gimeno-García et al., 2007). Immediately after the 2003 fire, however, the soil losses became directly influenced by the rainfall pattern. Indeed, the first post-fire rainfall event (I_{30} of 65.4 mm h^{-1}) led to a sediment yield of 3.19 T ha^{-1} on the burnt plots, representing 70% of the total yield for the first six months after the fire (period II). Also, during the two consecutives rainfall events (I_{30} of 35.6 mm h^{-1} and 91.8 mm h^{-1}) in the next year (2004), the erosion rate reached 3.6 T ha^{-1}, which represented 98% of the sediment loss during period IV. By contrast, soil loss in the control treatment (T3) was insignificant. Soto et al. (1994), in a two years study after a controlled fire, measured 90% of soil loss in only one rainfall event of 26 mm h^{-1}. Campo et al. (2006), at the same experimental station, measured

1.8 T ha^{-1} during the early rainfall event after the 1995 experimental fire. Thus, as indicated by Benavides-Solorio and MacDonald (2005), stronger rainstorms (high I_{30} levels) can initiate post-fire erosion even when there is relatively little bare soil.

The erosion rates measured in period II after the repeated fire (4.6 T ha^{-1} in the burnt plots and 0.0068 T ha^{-1} on the control plots), were comparable to those obtained by Inbar et al. (1998) and Campo et al. (2006), where under natural storms, which occurred within the first year after fire, describe a two order of magnitude increase in the erosion rates. Similar soil losses have been measured after a fire impact in Mediterranean environments. Mayor et al. (2007), calculated an erosion rate of 3.5 T ha^{-1} yr^{-1} in a *Pinus halepensis* burnt forest in Alacant (Southeast Spain). Seventeenth months after the first fire in 1995 at the La Concordia station, Gimeno-García et al. (2000) obtained soil losses from 3.2 to 4.1 T ha^{-1} in T2 and T1, respectively.

The low levels of sediment yield during period III may be related to the fact that the typical time between two consecutive rainfall events was only a few days (Fig. 2). This situation led to a less variable soil moisture regime, and together with the weak rainfalls recorded, higher infiltration rates were kept and thus erosion was limited. Benavides-Solorio and MacDonald (2001) also found an inverse relationship between soil moisture and sediment production after high severity fires.

Therefore, one reason of the enhanced soil erosion after the 2003 fire is the soil surface morphological change that reduced the litter and aboveground standing biomass (Imeson et al., 1992). This fact, together with the high rainfall intensity and the short time between the fire and heavy storms were the key factors of the increased runoff and sediment production.

4.3. Statistical relationship between erosion and rainfall characteristics

The statistical relationships between rainfall characteristics and the erosive parameters have shown the importance of the fire season relative to the erosive response. Intensive rainfalls in the Mediterranean area are concentrated in summer and autumn, the months with frequent forest fires. A wildfire impact before the high intensity storms could cause environmental degradation due to the produced runoff and soil losses. This temporal rainfall concentration is a relevant factor affecting soil erosion in this type of ecosystem (González-Pelayo et al., 2006).

Statistical analysis showed positive correlations of runoff and soil loss with rainfall intensity, only in the months when high I_{30} values were recorded (Tables 2 and 3). As indicated by Andreu et al. (2002), rainfall intensity is the decisive factor controlling soil loss on burnt plots, and rainfall volume must be a secondary factor on erosion in a post-fire Mediterranean ecosystem.

The relationships of rainfall intensity with runoff and sediment yield (Fig. 5) show significant correlations ($p < 0.05$). The rainfall intensity threshold, where the erosive processes were magnified in one order of magnitude, was around 20 mm h^{-1}. In the same study area, Gimeno-García et al. (2007) attributed 96% of soil losses to five rainfall events with I_{30} exceeding 20 mm h^{-1} during the first post-fire year. Castillo et al. (1997) measured the maximum soil losses in plots without vegetation when rainfall intensity was more than 20 mm h^{-1}. Like these studies, in our plots, 98% of soil loss after the 2003 fire was produced in response to four rainfall events with I_{30} exceeding 20 mm h^{-1}. Similarly, one year after the 2003 fire (period IV), two rainfall events with I_{30} > 20 mm h^{-1} explained 98% of the soil loss. Therefore, I_{30} > 20 mm h^{-1} may exceed the average infiltration rate of the burned soil, or exceed the level when runoff becomes dominated by sheet flow (Moody and Martin, 2001a). In other burnt areas, the threshold can be different. For example, Inbar et al. (1998), Moody and Martin (2001b) and Kunze and Stednick (2006) identified a threshold I_{30} value of 10 mm h^{-1}.

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4.4. Soil recovery

The magnitude of post-fire erosive responses can be quantified in terms of the change in hydrologic processes from that found under the unburnt pre-fire conditions (Cerdà and Lasanta, 2005). During the initial phase, erosion rates increase with time and reach a maximum, and during the recovery phase, they decrease; the duration of these two phases constitutes the relaxation–recovery time (Moody and Martin, 2001a,b). In the first post-fire year (1995–1996), the sediment yield from the burnt plots in the study area was 4.3 T ha^{-1} yr^{-1} (Gimeno-García et al., 2007), while in 2002–2003 (period I), it was 0.021 T ha^{-1}, a two order of magnitude diminution after eight years of soil and vegetation recovery. Inbar et al. (1998) reported, after three years of the Mont Carmel fire (Israel), a three orders of magnitude diminution of the sediment yield compared to the ones obtained in the first post-fire year.

The erosion data suggest that at the time of the repeated fire (July 2003), the soil-vegetation system was in the recovery stage, with decreasing rates of soil loss toward the pre-fire levels. The repeated fire in 2003 led the system into a degradation stage, increasing the relaxation–recovery time and erosion rates (Fig. 6). A parameter that quantifies the erosive response after fire impact is the erosion rate ratio (*ERR*), the ratio of burnt to non-burnt soil losses (Cerdà and Lasanta, 2005). In period II, average *EER* was 248. In the next year (period IV), it decreased to 148 (Fig. 6), although the differences between the burnt and control plots were still of two orders of magnitude. This reduction could be facilitated by soil consolidation and trapping of particles by vegetation (Inbar et al., 1998), and also by the rainfall characteristics; four consecutive heavy storms in the period II while two in period IV.

The time period to return to the steady-state conditions varies depending on several factors such as fire severity (Robichaud et al., 2000), the recurrence period of aggressive rainstorms (Benavides-Solorio and MacDonald, 2005), the soil water content related to the soil infiltration rate (Robichaud, 2000) and thus, on runoff and sediment yield. As noted, Moody and Martin (2001a) suggested three to four years as the relaxation time for sediment concentration. Robichaud et al. (2000) also reported a similar relaxation time under other environmental conditions, and Inbar et al. (1998), estimated a time of five to ten years. Hence, in our study area, erosion and sediment yield were already at the pre-fire level before the 2003 fire. However, total runoff yield was still four times greater than that of the control plots (Gimeno-García et al., 2007). The impact of a new fire in summer highlighted the soil susceptibility to erosion. Runoff and sediment yield significantly increased in response to intense rainstorms during the first two rainy seasons (Tables 2 and 3 and Fig. 5). This

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observation agrees with Benavides-Solorio and MacDonald (2001) in that soil loss in Mediterranean areas,is mainly related to torrential rainfalls after fire when vegetation cover is very thin.

5. Conclusions

This study has investigated change in vegetation, runoff and sediment yield in a Mediterranean-shrub ecosystem subject to experimental fire twice. A comparison between burnt and unburnt plots is also made. The first fire occurred in 1995, and eight years later vegetation recovery and top-soil improvement led to reduced erosion rates, almost reaching the condition before the burning. However, after the second fire in 2003, rainfalls of high intensity resulted in marked increase in runoff yield on the burnt plots, from 6.5 to 23.9 L m^{-2}. Soil loss and sediment delivery also significantly increased from 0.021 T ha^{-1} to 4.6 T ha^{-1}, due to degraded vegetation cover and increased bare soil surfaces.

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During the duration of the study (March 2002–December 2004), four periods were statistically differentiated according to the characteristics of rainfalls, mainly intensity and duration. Significant linear correlations ($R^2 > 0.8$) between I_{30} values, runoff and soil loss in the burnt plots were found, showing that soil erosion was accelerated due to heavy rainfalls. One year after the second fire, the soil loss difference between the burnt and control plots was still of two orders of magnitude. The ratio of the erosion rate at the burnt plots and that of the control plots decreased from 248 (period II) to 148 (period IV), which could be explained mainly by a few higher intensity rainstorms during period IV.

The first two rainy seasons with intense storms after the 2003 fire were the periods when the soil was more prone to erosion. Rainfall intensity exceeding 20 mm h^{-1} significantly enhanced runoff and soil loss in the burnt plots. Such heavy and infrequent rainfall events produced over 90% of the total sediment yield during 18 months after the 2003 fire. To summarize, in a Mediterranean-shrub ecosystem, repeated fire events at least every eight years could cause progressive degradation and increase the risk of desertification.

Acknowledgements

We thank the financial support from the Convenio Generalitat Valenciana - CSIC (2006□2009) “Impacto de los incendios forestales repetidos sobre los procesos de erosión hídrica del suelo y la recuperación de la cubierta vegetal. Seguimiento y evaluación en una estación permanente de campo” (2005020112). We also thank Hugh A. Malem for improving the English.

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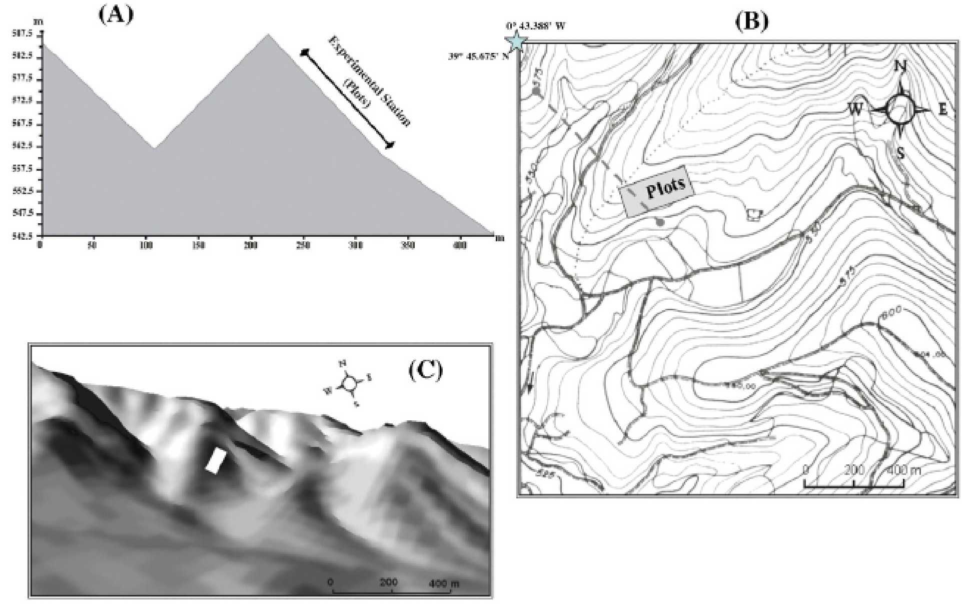

Fig. 1. Morphological characteristics of the study area. (A) Topographic profile. Location is shown in (B). (B) Topographic map. Grey broken line indicates the profile in (A). (C) Bird eye's view from a digital terrain model with the location of the plots (white rectangle)

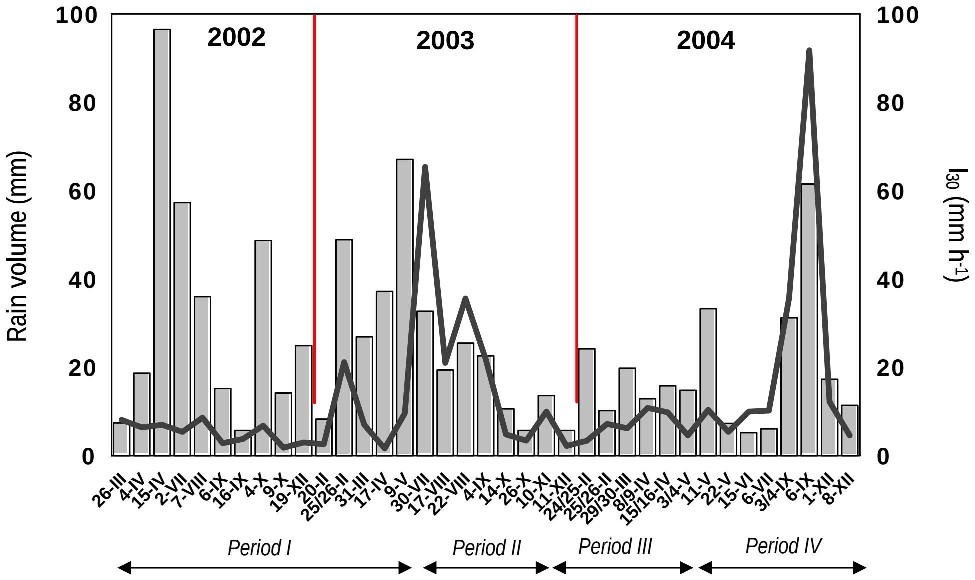

Fig. 2. Erosive rainfall events occurred during the studied period (rain volume in bars and I_{30} in line).

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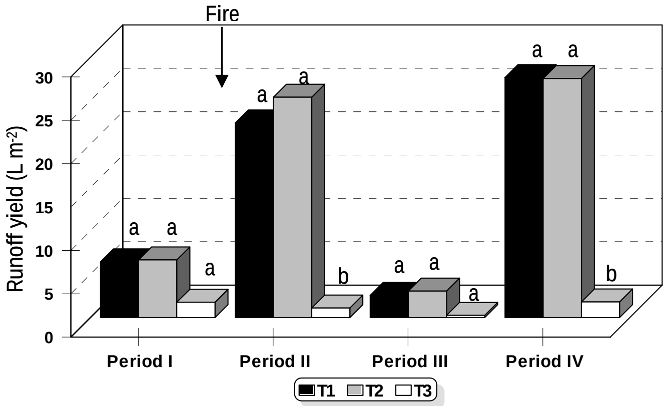

Fig. 3. Runoff yield (L m^{-2}) recorded during 37 rainfall events. Values not sharing the same letter within each period indicate statistically significant differences according to Tukey´s test (p < 0.05). T1 = high fire severity, T2 = moderate fire severity, T3 = control.

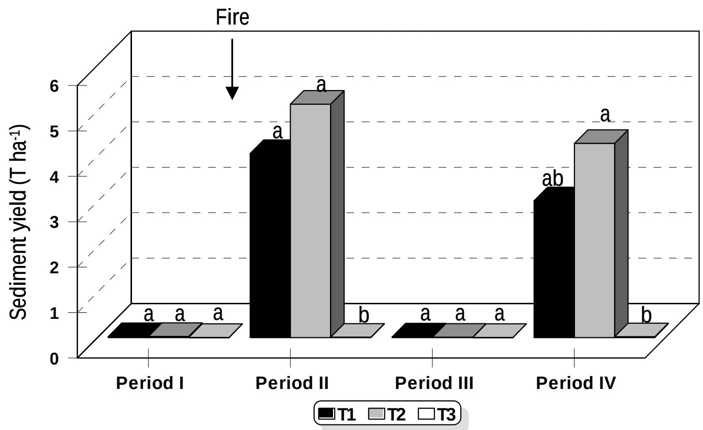

Fig. 4. Sediment yield (T ha^{-1}) collected during 37 rainfall events. Values not sharing the same letter within each period indicate statistically significant differences according to Tukey´s test (p < 0.05). T1 = high fire severity, T2 = moderate fire severity, T3 = control.

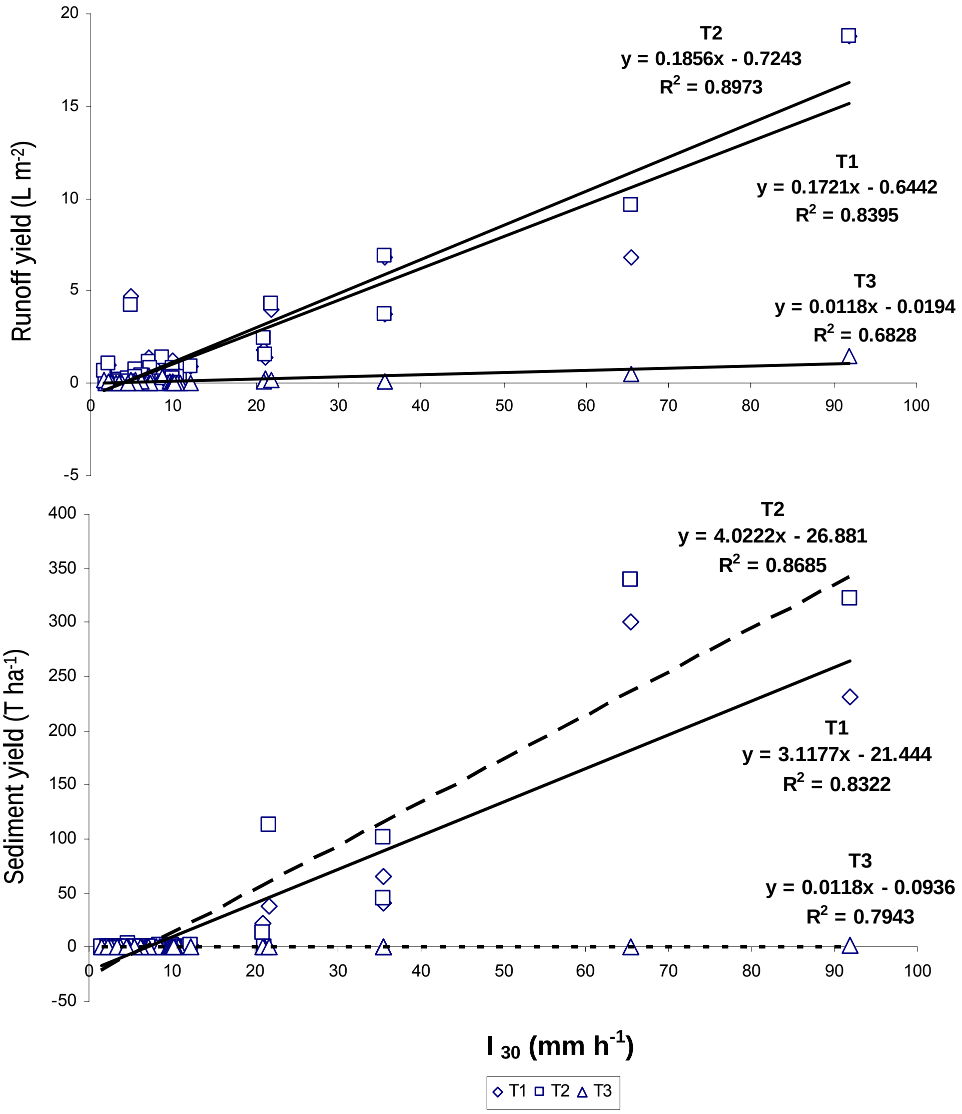

Fig. 5. Statistical relationships (p < 0.05) between runoff yield, sediment yield and average I_{30} for the whole studied period. n = 37. T1 = high fire severity, T2 = moderate fire severity, T3 = control.

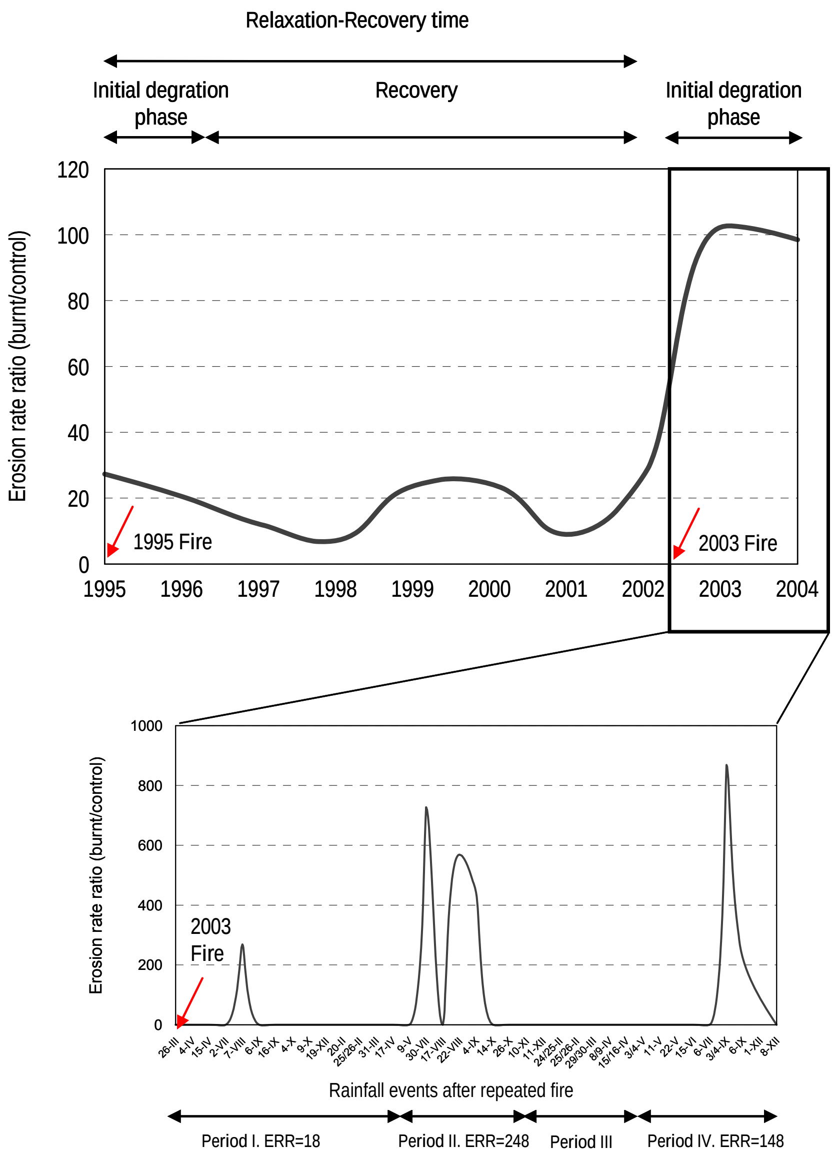

Fig. 6. Erosion rate ratio (*ERR*) after the 1995 and 2003 fire events.

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Table 1. Erosive rainfall characteristics of the defined periods. Values not sharing the same letter in rows indicate statistical significant differences between periods, using Tukey´s test (*p<0.05*)

Season	2002-spring 2003	Summer-autumn 2003	Winter 2003-spring 2004	Summer-autumn 2004
Periods	I	II	III	IV
Total rain volume (mm)	759 a	227 b	274 b	191 b
Erosive rain volume (mm)	513 a	130 b	103 b	173 b
Number of erosive rain events	15	7	7	8
Average I_{30} (mm h^{-1})	6.4 a	23.14 b	6.31 a	22.5 b
Range of variation of I_{30} (mm h^{-1})	1.8-21.2	3.4-65.4	2.2-10.8	4.6-91.8
Mean Duration (minutes)	1436.4 a	242.5 b	1029.1 a	419.75 b
Range of variation of rain duration (minutes)	185-5450	30-580	620-1420	38-770

Table 2. Pearson´s correlations coefficients between rainfall parameters (rain volume, duration, I_{30}) and runoff yield, calculated by treatments, on the whole studied period (2002-2004), and on each defined one. T1, high fire severity; T2, moderate fire severity; T3, control

	Period	Treatment	Rain volume	Duration	I_{30}
Runoff yield	2002-2004	T1	0.327*	-0.164 (ns)	0.916**
	(n=37)	T2	0.319 (ns)	-0.180(ns)	0.947**
		T3	0.546*	0.310 (ns)	0.826**
	I *(n=15)*	T1	0.684**	0.192 (ns)	0.602*
		T2	0.625*	0.124 (ns)	0.647*
		T3	0.772**	0.295 (ns)	0.392 (ns)
	II *(n=7)*	T1	0.737(ns)	-0.359 (ns)	0.738 (ns)
		T2	0.811*	-0.466 (ns)	0.862*
		T3	0.691(ns)	-0.518 (ns)	0.826*
	III *(n=7)*	T1	-0.829 (ns)	-0.451(ns)	-0.375 (ns)
		T2	-0.793 (ns)	-0.422 (ns)	-0.341 (ns)
		T3	-0.53 (ns)	-0.267 (ns)	-0.292 (ns)
	IV (*n=8)*	T1	0.895*	-0.003 (ns)	0.997*
		T2	0.890*	-0.011 (ns)	0.997*
		T3	0.858*	0.107 (ns)	0.964*

* Positive correlation at 0.05 level. ** Positive correlation at 0.01 level. (ns) Non significance

Table 3. Pearson's correlations coefficients between rainfall parameters (rain volume, duration, I_{30}) and sediment yield, calculated by treatments, on the whole studied period (2002-2004), and on each defined one. T1, high fire severity; T2, moderate fire severity; T3, control

	Period	Treatment	Rain volume	Duration	I_{30}
Sediment yield	2002-2004	T1	0.241 (ns)	-0.184 (ns)	0.912**
	(n=37)	T2	0.256 (ns)	-0.182 (ns)	0.932**
		T3	0.312 (ns)	-0.113 (ns)	0.891**
	I *(n=15)*	T1	0.097 (ns)	-0.249 (ns)	0.268 (ns)
		T2	0.104 (ns)	-0.252 (ns)	0.238 (ns)
		T3	0.019 (ns)	-0.219 (ns)	0.127 (ns)
	II *(n=7)*	T1	0.772*	-0.528 (ns)	0.920*
		T2	0.800*	-0.358 (ns)	0.904*
		T3	0.811*	-0.291 (ns)	0.901*
	III *(n=7)*	T1	0 (ns)	-0.252 (ns)	0.028 (ns)
		T2	-0.367 (ns)	-0.452 (ns)	-0.047 (ns)
		T3	0 (ns)	0 (ns)	0 (ns)
	IV (*n=8)*	T1	0.881**	0.001 (ns)	0.996**
		T2	0.884**	-0.011 (ns)	0.996**
		T3	0.852**	0.083 (ns)	0.969**

* Positive correlation at 0.05 level. ** Positive correlation at 0.01 level. (ns) Non significance